Simulation of Error-Induced Beam Degradation in the FNAL-Booster

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Physics Motivations

1. Explore phenomena induced by unavoidable systematic and random machine errors, or imperfections in the Booster that may generate continuous emittance growth and halo formation.

2. Searching for other general sources of halo formation in synchrotrons, or storage rings.

3. Since analytic predictions are somewhat limited, reliable, and realistic 2-D or 3-D simulations are needed to study halo formation and beam degradation in rings.

4. Building realism into the ORBIT-FNAL package.

New Noise Module

- New object-oriented Noise module has been incorporated into the ORBIT-FNAL package.

- The major features of the noise module:
  - Generates different types (dynamic and static) of random Gaussian-driven noise around the synchrotron.

  - Calculate halo amplitudes, RMS transverse emittances, beam loss, and statistical properties of random noise.

  - Noise strength can be controlled over in an input script file.
  - Parallelized with MPI (Message Passing Interface).
  - Exceptions and Error Handling

Simulation Parameters

- MAD Lattice: FNAL-BST Lattice
- Ring Circumference: 474.204810 (m)
- Beam Kinetic Energy: 400 (MeV)
- β_R : 0.7131
- γ_R : 1.4263
- τ_{REV} : 2.2 (μsec)
- γ_{TR}: 5.4696
- $|\eta|$ at Injection: 0.458
- β_x / β_y: 7.303 / 20.0232 (m)
- α_x/ α_y : 0.214 / -0.180 (m)
- Φ_{min}/Φ_{max}: -100.0/100.0 (deg.)
- ε_x/ ε_y = 5.0/5.0 (π-mm-mrad)
- RF Voltage: 205.0 (KV/Turn)
- Tail Fraction = 0.0
- Transverse Distribution: bi-Gaussian
- Longitudinal Distribution:
  Uniform Distribution

- Max. No. of MacroParticles : 100K
- Injection Turns: 10
- Total Proton Intensity: 6.00E+11 (ppb)
- RF Harmonics: 1
- FNAL-BST Harmonic No.: 84
- RF Phase = 0.0 (deg.)
- Tracking Turns after Injection: 1K
- ν_x/ ν_y (nominal tunes): 6.7/6.8
- Q_s: 0.04295
- Space Charge: 2.5 D
- No. of Longitudinal Bins: 32
- No. of Transverse Bins: 64

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Building Realism into ORBIT-FNAL

- The following perturbations are reflected in simulation:

- Magnetic alignment errors
  1. Transverse Error
  2. Longitudinal Error
  3. Rotational Errors (XY, XS, and YS)

- Transverse / Longitudinal Space-Charge Forces
- Power-Supply Ripples: $\Delta I / I < \sim 10^{-4}$

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Power Supply Ripples

$$K_{n,id} = \left(\frac{B_n}{B\rho \cdot I_{id}} \right) \cdot I_{id} = K_{Q,id} \cdot I_{id}$$

$$K_{n,real} = \left(\frac{B_n}{B\rho \cdot I_{id}} \right) \cdot I_{real} = K_{Q,id} \cdot I_{real}$$

$$\Delta K_n \equiv K_{n,real} - K_{n,id} = K_n \cdot \left(\frac{\Delta I}{I} \right)$$

$$\therefore \quad \frac{\Delta I}{I} = \frac{\Delta B}{B} = \left(\frac{\Delta K_n}{K_n} \right)$$

$$\theta_F = \Delta K_{1,F} \cdot \Delta x_F \cdot L_Q \approx 2(\mu rad)$$

$$\theta_D = \Delta K_{1,D} \cdot \Delta x_D \cdot L_Q \approx 1(\mu rad)$$

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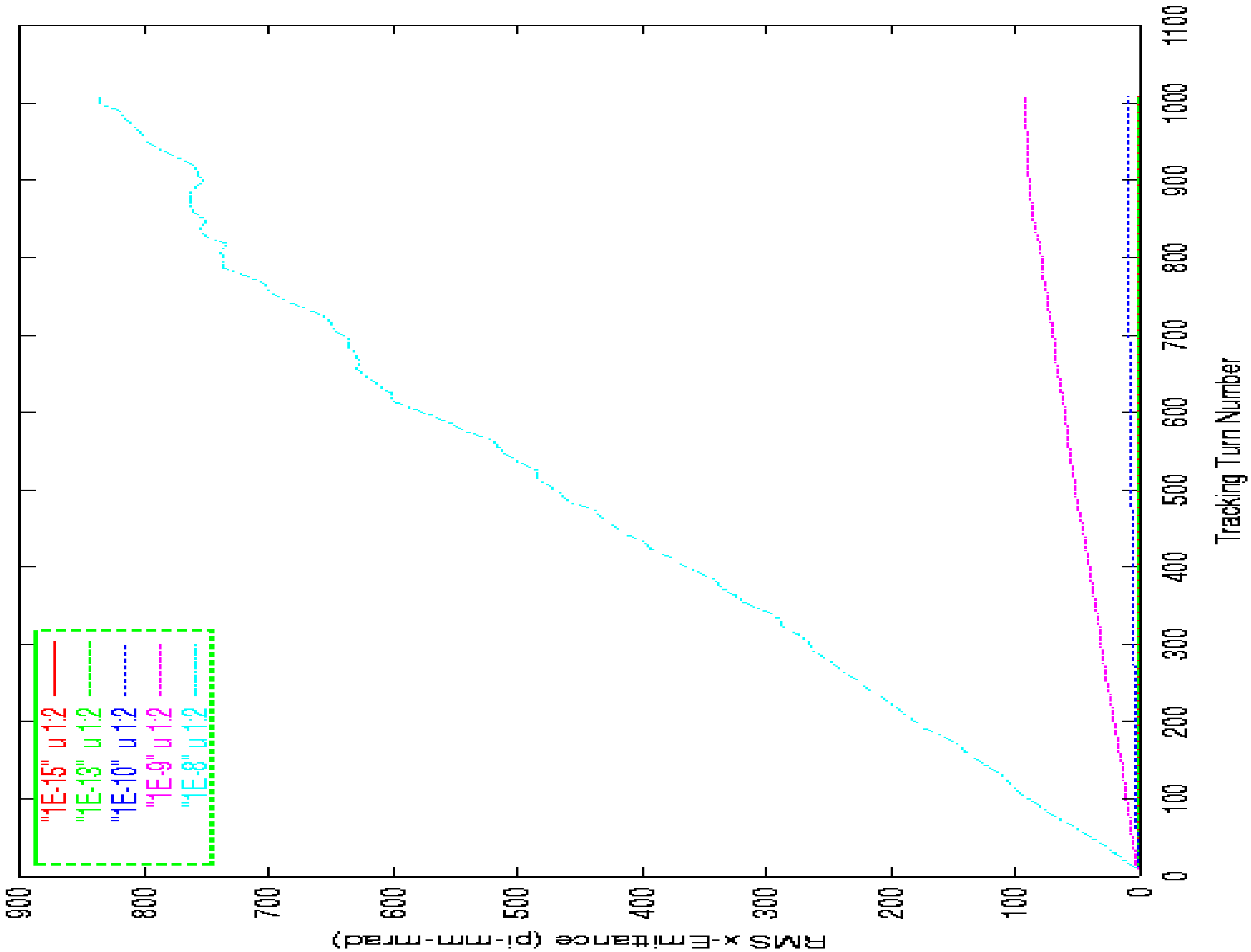
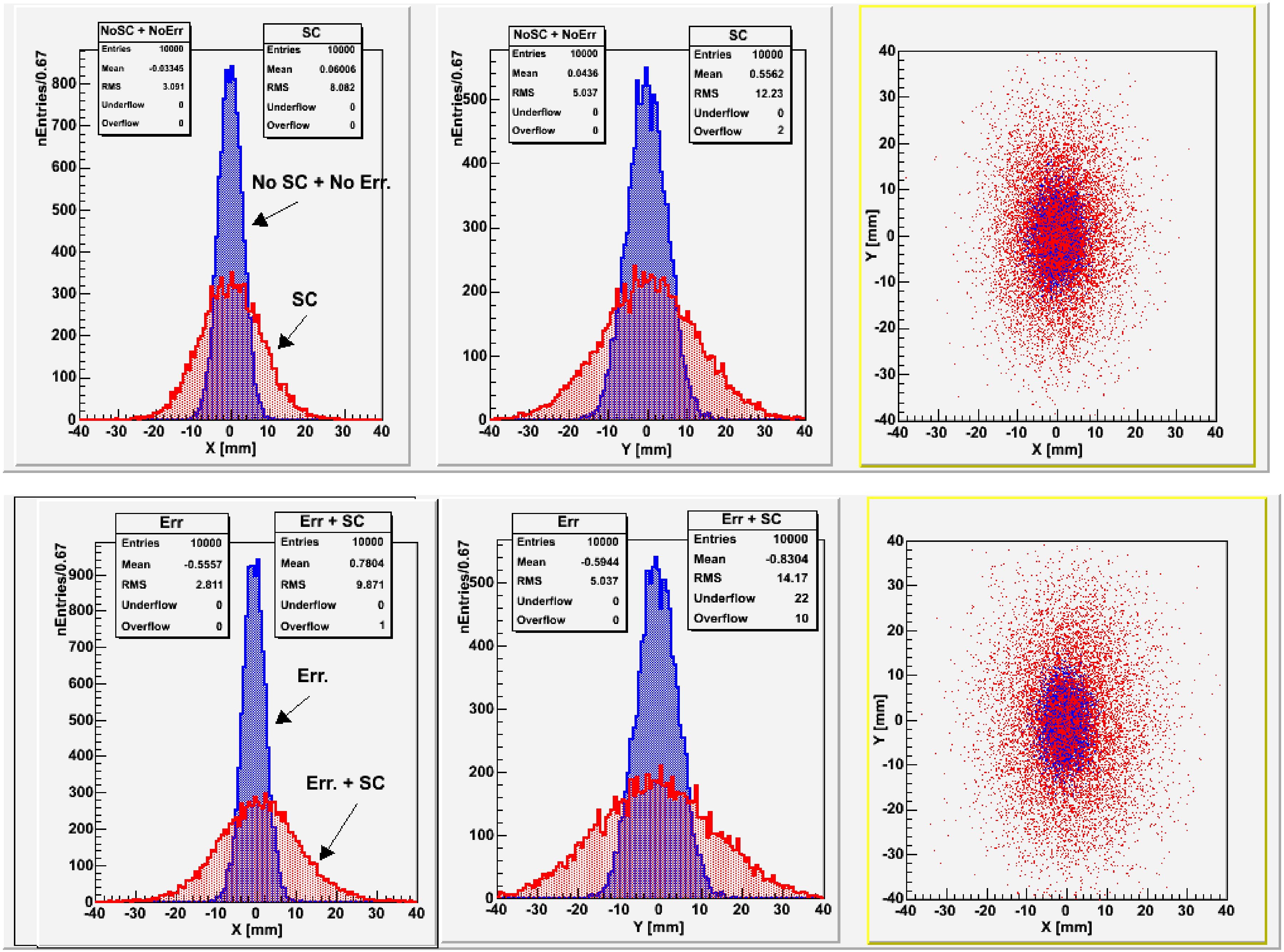
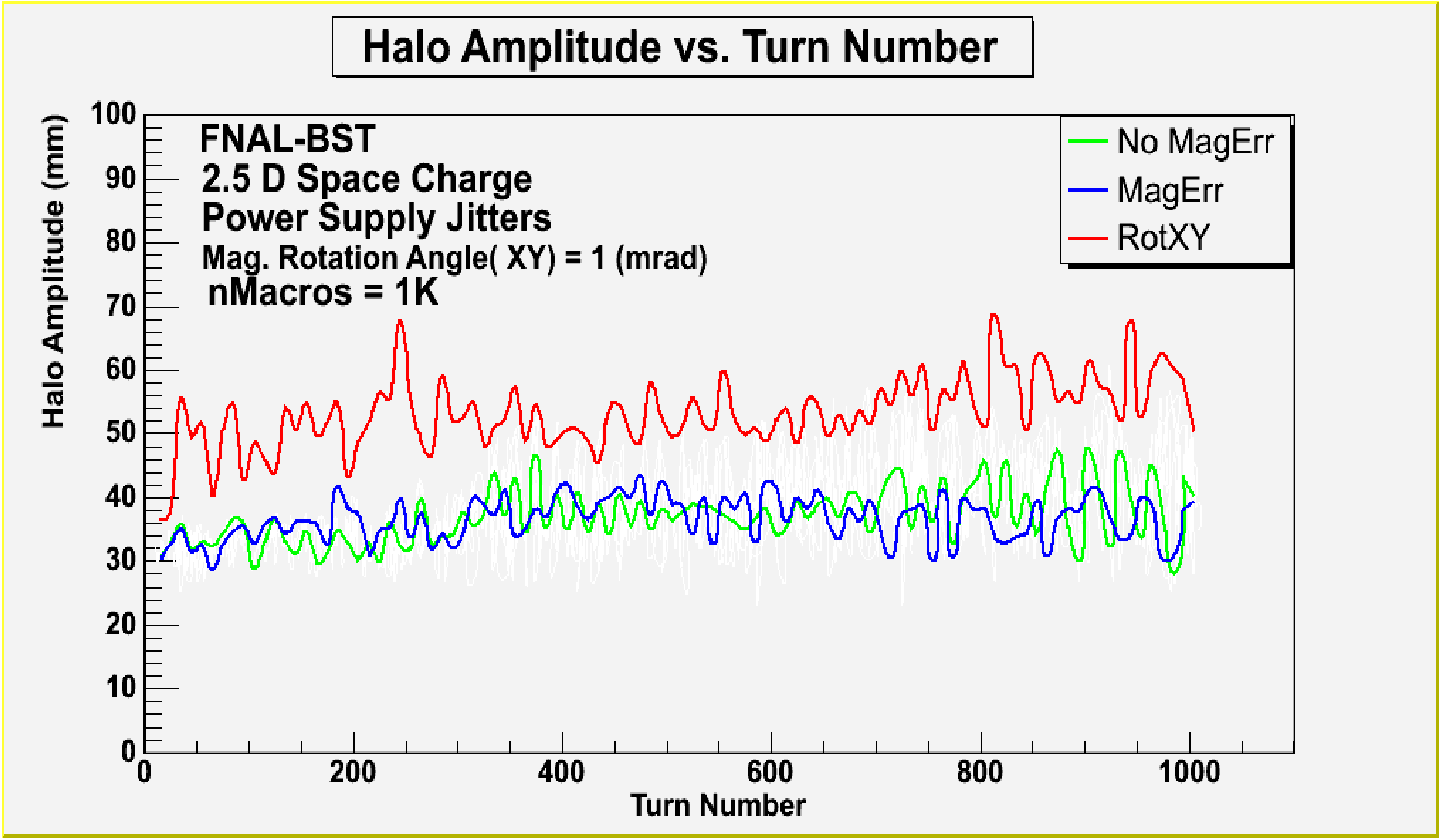
"1E-15" u 1:11
"1E-13" u 1:11
"1E-10" u 1:11
"1E-9" u 1:11
"1E-8" u 1:11
Halo Amplitude [mm]
Tracking Turn Number
0
50
100
150
200
250
300
0
100
200
300
400
500
600
700
800
900
1000
1100



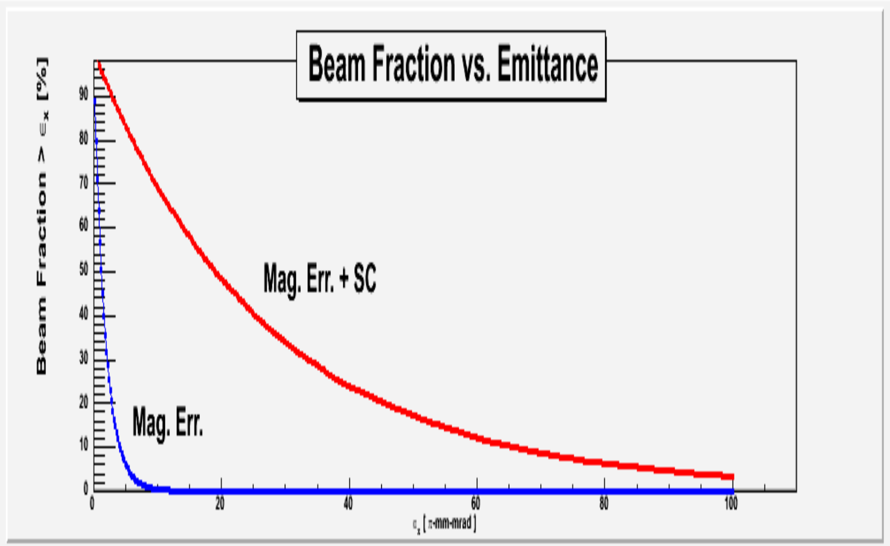
RMS x-Emittance (pi-mm-mrad)
Tracking Turn Number
0
100
200
300
400
500
600
700
800
900
1000
1100
"1E-15" u 1:2
"1E-13" u 1:2
"1E-10" u 1:2
"1E-9" u 1:2
"1E-8" u 1:2

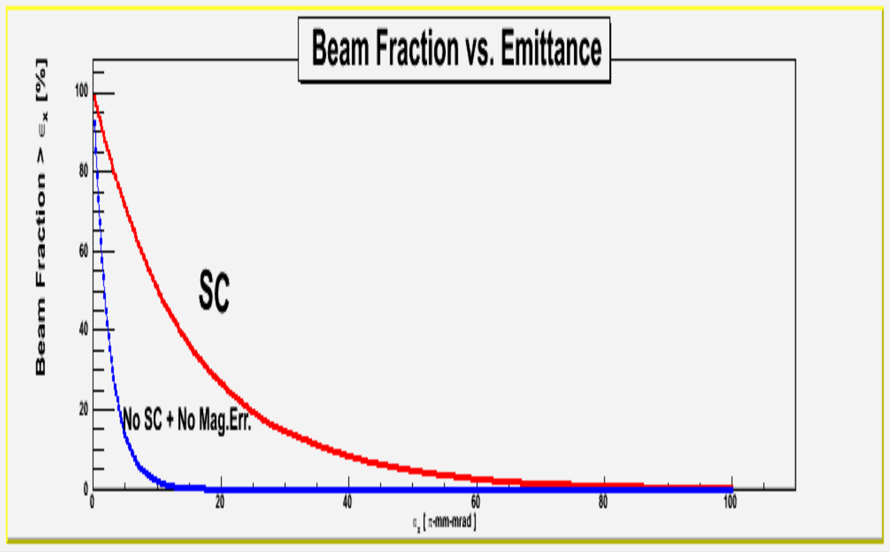

NoSC + NoErr
Entries 10000
Mean -0.03345
RMS 3.091
Underflow 0
Overflow 0
SC
Entries 10000
Mean 0.06006
RMS 8.082
Underflow 0
Overflow 0
No SC + No Err.
SC
nEntries/0.67
X [mm]
NoSC + NoErr
Entries 10000
Mean 0.0436
RMS 5.037
Underflow 0
Overflow 0
SC
Entries 10000
Mean 0.5562
RMS 12.23
Underflow 0
Overflow 2
nEntries/0.67
Y [mm]
Y [mm]
X [mm]
Err
Entries 10000
Mean -0.5557
RMS 2.811
Underflow 0
Overflow 0
Err + SC
Entries 10000
Mean 0.7804
RMS 9.871
Underflow 0
Overflow 1
Err.
Err. + SC
nEntries/0.67
X [mm]
Err
Entries 10000
Mean -0.5944
RMS 5.037
Underflow 0
Overflow 0
Err + SC
Entries 10000
Mean -0.8304
RMS 14.17
Underflow 22
Overflow 10
nEntries/0.67
Y [mm]
Y [mm]
X [mm]

Halo Amplitude Growth



Transverse Emittance Distribution



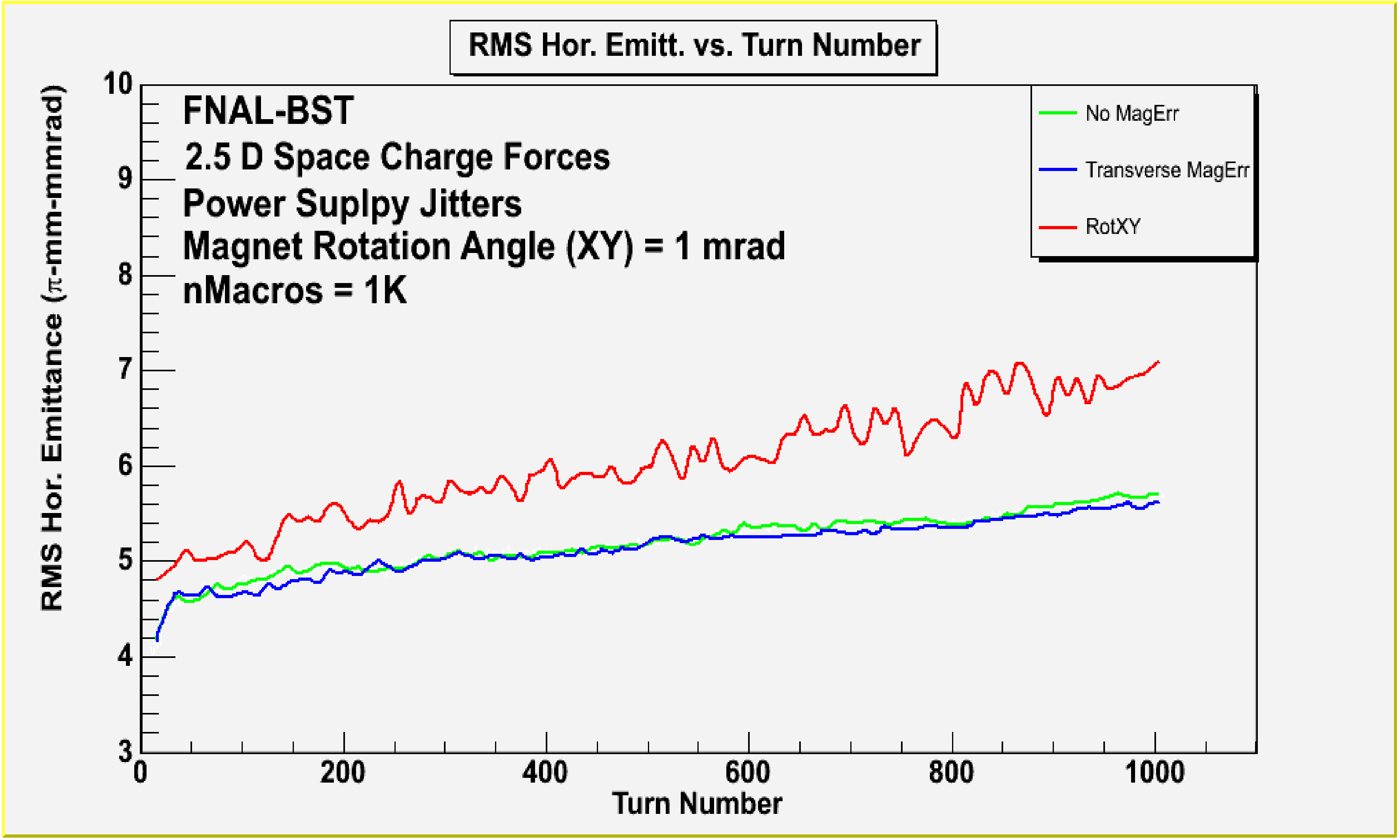


- In order to quantify the amount of halo in a distribution, the fraction of particles outside

  N times its RMS emittance in each plane is plotted.

  Thus, the development of beam halo can be clearly separated from ε_{rms} growth.

Transverse Emittance Growth



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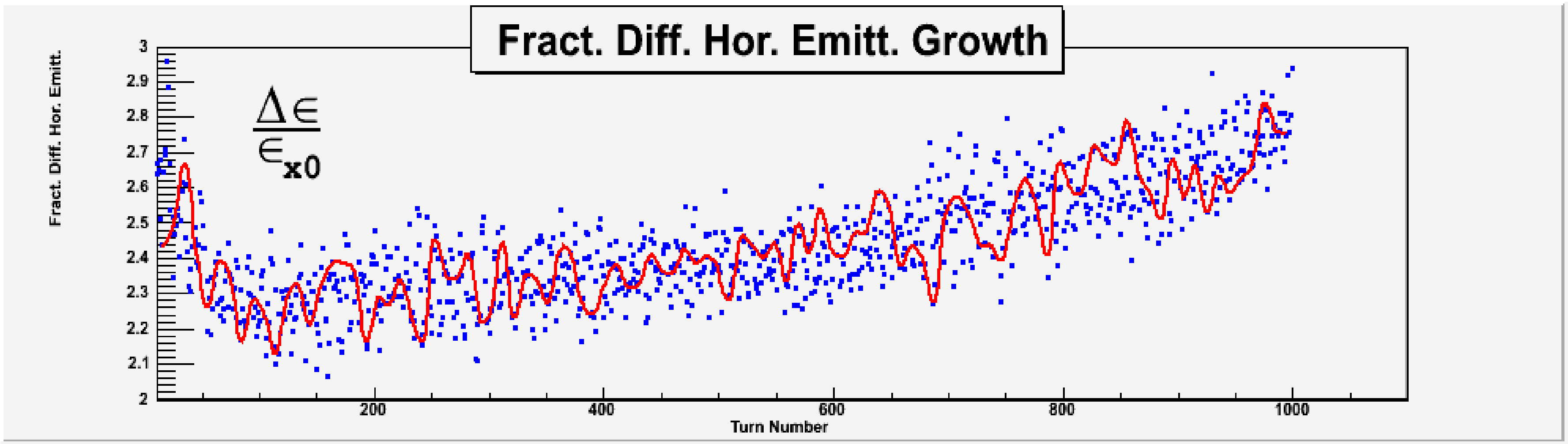
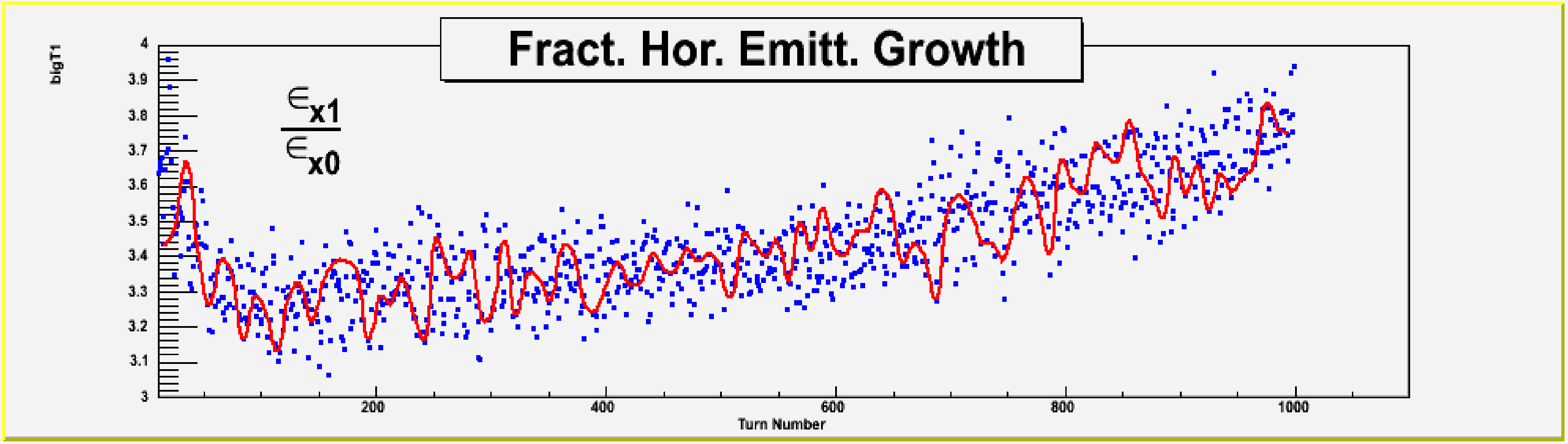
Transverse Emittance Growth Rate





Observed Trends

- The Simulation shows that the following is sources of beam degradation and halo formation.

  (1) Magnet alignment errors in presence of space charge effects.
  Rotational alignment errors induce more rapid
  halo and tail formations and transverse emittance growth.

  (2) Power-Supply Jitters

  (3) Beam Emittance Mismatch:
  Its contribution to halo formation appears to be insignificant.

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What's Next?

- So far, transverse beam dynamics (2-D motion) has been investigated.
- Simulation with sufficiently large number of macroparticles (~ 1M)
- Planning to look into the other missing dimension (longitudinal beam dynamics).

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Planned Runs

Number of Macros	Translational Errors	Longitudinal Errors	Rotational Errors	Space Charge
100 K			X-Y	2.5D
100 K			X-S / Y-S	2.5D
100 K	X/Y			2.5D
100 K		S		2.5D

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